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16. ABSTRACT

Plume rise calculations are based on the equations of Briggs (1975) for use with variable vertical profiles of temperature and wind speed. Results are presented for small and large chimneys, based on five years of twice-daily rawinsondes throughout the contiguous United States. In addition to effective chimney heights, data are also generated on the frequencies of plume center-lines below, within, or above an inversion, and when they were reached by the afternoon mixing height. The data show quantitatively that initially the effluent from large chimneys tends to remain airborne longer than from small chimneys.

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CLIMATIC DATA ON ESTIMATED EFFECTIVE CHIMNEY HEIGHTS IN THE UNITED STATES

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1. INTRODUCTION

A very important step in calculating ground-level concentrations of pollutants emitted from chimneys is determining the effective chimney heights or, as defined in this paper, the equilibrium heights of initially buoyant plumes. The significance of this matter is easily recognized since, as a very general rule, ground-level concentrations vary inversely as the square of the plume height above the ground. Until the monograph by Briggs (1969), supported later by his refined and expanded version (1975), there was great controversy about the most accurate, generally applicable formulation for plume rise. While some disagreement continues and additional developmental work remains, Briggs' equations are now used widely. In such applications it has become common practice (e.g., Turner, 1973), dictated largely by necessity, to assume that stability and wind conditions near ground-level extend throughout the atmosphere through which a plume rises - although it is clearly recognized that plume rise is highly dependent upon the wind and stability structure of the air surrounding the plume. The purpose of this paper is to present climatological data on effective chimney heights and plume behavior, based on 5 years of twice-daily rawinsonde observations from 62 National Weather Service stations in the contiguous United States. These data are limited to hypothesized small and large chimneys in order to contrast the results.

2. METHODOLOGY

Calculations of plume rise in this study are based upon the formulae of Briggs (1975, Eqs. 74 and 75) for rise through vertically varying profiles of temperature and wind speed. The main assumptions are that buoyancy dominates the rise and is conserved so that the motion is adiabatic, mass and momentum are conserved, plumes are either nearly horizontal or nearly vertical, and the entrainment velocity is proportional to shear between the plume and the surrounding air. In Briggs' method of calculating plume rise the buoyancy flux of a plume segment is followed through successive layers, where it is depleted (or enhanced), to the level where the flux is zero. The buoyancy flux from the chimney (F_o, m^3 sec^{-1}), assuming standard conditions#, is

$$F_o = 3.7 \times 10^{-5} Q_H \qquad (1)$$

The heat emission rate (Q_H) is determined from

$$Q_H = 83.45\, Q_V P_o \frac{T_s - T_o}{T_s} \quad (\text{cal sec}^{-1}) \qquad (2)$$

where

Q_V = gas volume emission rate from chimney (m sec^{-1})
P_o = atmospheric pressure at top of chimney (mb)
T_s = effluent temperature at top of chimney (K)
T_c = air temperature at top of chimney (K)

Q_V and T_S are specified, while P_o and T_o are determined from the rawinsonde data. Each sounding is divided into successively higher layers in which the change of temperature with height ($\Delta T/\Delta Z$, C m^{-1}) and wind speed ($\Delta U/\Delta Z$, sec^{-1}) both are constant. The height above the chimney top of the bottom of each layer is specified as Z_{n-1} and the top of each layer is specified as Z_n. Thus, the chimney top is at the bottom of the lowest layer, where $Z_{n-1} = 0$ and F_o becomes F_{n-1}. The buoyancy flux at the top (F_n) of each successively higher layer is calculated until it becomes negative. At that level F_n is set equal to zero and the equation is re-solved for the plume rise (Z_e) above the chimney top. The effective chimney height equals the physical chimney height plus the plume rise.

* On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

This assumption results in a somewhat conservative estimate of F_o for high-altitude stations. The correction factor is $(1000 \div P_o)$.

The first set of equations for calculating F_n and Z_e is for no-wind conditions, i.e., nearly vertically rising plumes,

$$F_n = F_{n-1} - \frac{.265F_o^{1/3}}{273+.5(T_n+T_{n-1})}\left(\frac{T_n-T_{n-1}}{Z_n-Z_{n-1}}+.01\right)\left(Z_n^{8/3}-Z_{n-1}^{8/3}\right) \quad (3)$$

$$Z_e = \left\{Z_{n-1}^{8/3}+3.77\left(\frac{F_{n-1}}{F_o^{1/3}}\right)(273+T_{n-1})\left[\frac{Z_n-Z_{n-1}}{T_n-T_{n-1}+.01(Z_n-Z_{n-1})}\right]\right\}^{3/8} \quad (4)$$

where T (C) is air temperature and Z (m) is height above the chimney top. In Eq. (4) $273+T_{n-1}$ is used instead of $273+.5(T_n+T_{n-1})$. As described earlier, Eq. (4) evolves from Eq. (3) by setting $F_n = 0$ and $Z_n^{8/3} = Z_e^{8/3}$; the Z_n notation in the ratio, $\frac{T_n-T_{n-1}}{Z_n-Z_{n-1}}$, is retained since the value is by definition constant through the entire layer. The numerical constant, 0.265, in Eq. (3) includes the appropriate entrainment coefficient and gravity (see Briggs, 1975).

The second set of equations is for with-wind conditions, i.e., nearly horizontally rising plumes,

$$F_n = F_{n-1} - \frac{.523}{273+.5(T_n+T_{n-1})}\left(\frac{T_n-T_{n-1}}{Z_n-Z_{n-1}}+.01\right)\left[.5(U_n+U_{n-1})\right]\left(Z_n^3-Z_{n-1}^3\right) \quad (5)$$

$$Z_{e1} = \left\{Z_{r-1}^3+\frac{1.91F_{n-1}(273+T_{n-1})}{U_{n-1}}\left[\frac{Z_n-Z_{n-1}}{T_n-T_{n-1}+.01(Z_n-Z_{n-1}}\right]\right\}^{1/3} \quad (6)$$

$$Z_e = \left\{Z_{n-1}^3+\frac{1.91F_{n-1}}{.5(U_{n-1}+U_{e1}}\left[273+.5(T_{n-1}+T_{e1})\right]\left[\frac{Z_n-Z_{n-1}}{T_n-T_{n-1}+.01(Z_n-Z_{n-1})}\right]\right\}^{1/3} \quad (7)$$

where U is wind speed (m sec^{-1}). In Eq. (6) $273+T_{n-1}$ is used instead of $273+.5(T_n+T_{n-1})$ and U_{n-1} is used instead of $.5(U_n+U_{n-1})$. Z_{e1} is a preliminary estimate of the plume rise. This step is necessary because the Eq. (7) can be sensitive to the wind speed (U_{e1}) at the plume-rise height (i.e., at Z_{e1}).

Specification of sufficiently slow winds for use of the no-wind equations is somewhat arbitrary in some cases and is based on the personal recommendation of Briggs. For layers with U = 0.0 m sec^{-1} there is no ambiguity and the no-wind equations are used. For all other layers we interpolate to the level Z_{ub} at which the critical wind speed (U_b) occurs,

$$U_b = \left(\frac{.008F_o}{Z_n+Z_{n-1}}\right)^{1/3} \quad (8)$$

If U_b occurs in the particular layer, the no-wind equations are used in the sublayer with $U < U_b$ and the with-wind equations are used in the sublayer with $U \geq U_b$. If, in the particular layer, all $\overline{U} > U_b$, the with-wind equations are used for the entire layer; if all $U < U_b$, the no-wind equations are used. Ordinarily $U_b < 1.0$ m sec^{-1}, even for very large chimneys, and the no-wind equations are rarely used.

Effective chimney heights were calculated for several specified values of physical chimney height, corresponding volume emission rates, and effluent temperatures. National Weather Service rawinsonde observations, scheduled at 0000 and 1200 GMT during 1960-1964 at 62 locations in the contiguous United States, were used in the calculations. In addition to calculations of effective chimney heights, the behavior of the plumes was inferred from existing analyses of the temperature structure of each sounding (Holzworth, 1974b) and from the estimated mixing heights for each day (Holzworth, 1972). This paper focuses on the spatial distribution of annual data for small (50-m) and large (400-m) chimneys as well as a tabular summary for Salt Lake City. Data were also processed for 100-, 200-, and 300-m chimneys on a seasonal basis, but space limitations precluded the inclusion of those results in this paper. They will be presented later in an EPA publication.

Average values of volume emission rate (Q_v) and effluent temperature (T_s) used for each physical chimney height were based on a summary of United States power plant characteristics (Tikvart, 1976):

Chimney Height (m)	Q_v(m^3 sec^{-1})	T_s(K)
50	110	445
400	2000	410

Although actual chimney heights only now are approaching 400 m, the trend is clearly to large sizes. The comparison of results for the two chimney sizes should be indicative of behavior trends for any sources of comparable chimney height and heat emission rate. Also, the results for the two extreme chimney sizes may be interpolated to gain some rough idea of values for intermediate size chimneys.

3. RESULTS

The results presented in this paper are in tabular form for Salt Lake City and as isopleth analyses for the contiguous 48 States. Space limitations prevent showing the data for each station, but all of the data have been included in the analyses. Clearly, the data are most representative of each rawinsonde site (and observation time). The isopleth analyses, therefore, should be used cautiously, especially in areas of contrasting land-use and irregular terrain. The analyses are offered as general guidelines. The appropriateness of values between specific data points should be considered very carefully. For example, most rawinsonde stations are located in suburban or rural surroundings so consideration should be given to possible heat island effects, especially at night. Furthermore, none of the rawinsonde stations are located on isolated, relatively high terrain; most are in valleys. Therefore, the results presented for irregular terrain are applicable to valley locations. Nevertheless and with the foregoing limitation, the fact that the isopleth patterns are reasonably smooth suggests that the data are fairly representative on the scale at which the stations are spaced.

Although great progress has been made in developing and applying plume rise theory, much remains to be done. For example, the effective chimney height calculations in this paper are for plume centerlines, but in some configurations the plumes are likely to extend through considerable depths. Thus, in the case of a plume centerline penetrating into and/or through an inversion, such a description may apply to only some fraction of the plume. This problem and its possible solution have been discussed by Briggs (1975), although application at this time seems premature, especially in view of the current state of plume-rise verification.

a. Salt Lake City, Utah

Table 1 summarizes the data for Salt Lake City. The heat emission rates for 50- and 400-m chimneys differ by a factor of about fifteen, which is characteristic for all stations reported in this paper. At 0415 MST* the average effective height for small chimneys is 148 m and for large chimneys it is 752 m; the difference in average plume rise (98 and 352 m) is a factor of about three and one-half. This is caused not only by the difference in initial heat flux, but also by the fact that 400-m chimneys are usually above the top of radiation inversions that are very common in the region (Hosler, 1961). The range and standard deviation of effective heights at 0415 MST are considerably less for small than for large chimneys. The average effective heights with respect to the ranges and standard deviations indicate that the frequency distributions of effective heights are concentrated in the lower heights and tail off with higher heights.

At 1615 MST the average effective height for small chimneys is 356 m and for large chimneys it is 915 m. Compared to 0415 MST, the average afternoon height for small chimneys is more than double, but for large chimneys the increase is less than one-fourth. This is largely caused by the fact that at 1615 MST, especially during summer, the plumes from 50-m chimneys are emitted into a superadiabatic atmosphere (Holzworth, 1974a) from which they gain buoyancy as they rise. The plumes from 400-m chimneys, however, are usually above the superadiabatic layer. Other indications of this afternoon effect are the nearly equal upper limits of the ranges of effective heights and the nearly equal standard deviations for small and large chimneys.

At 0415 MST most of the centerlines of "small plumes" (67%) were in a temperature inversion, probably in a fanning configuration; 19% were above the inversion, probably in a weak fanning or lofting mode, depending on their proximity to the inversion top and the lapse rate. Only 5% of the small morning plumes were below an inversion, and since the lapse rates were usually subadiabatic, were likely in a weak fanning mode. There was no inversion below 3000 m† in only 9% of the 0415 MST observations. Practically all of the small morning plumes (97%) were subsequently reached by the afternoon mixing heights. This suggests that during some part of the intervening period the initially fanning plumes went through the fumigation process. Since the average afternoon mixing height of about 2300 m (Holzworth, 1972) is very large with respect to the average plume height (148 m), most fumigations were probably brief.

Most of the large plumes at 0415 MST (79%) were above an inversion and only 10% were in an inversion because, as suggested, most radiation inversions did not extend much above 400 m. Only 76% of the large morning plumes were subsequently reached by the afternoon mixing heights - in contrast to 97% for small plumes. These data clearly indicate that the effluent from large chimneys tends to remain airborne longer than that from small chimneys.

At 1615 MST there was no inversion in 70% of the soundings. It is likely that many of these plumes were in a looping mode through a deep layer, especially small plumes during summer, but coning was probably common also. The occurrence of afternoon plumes below an inversion (21% for small and 16% for large chimneys) suggests trapping conditions, which would be interesting to investigate in more detail.

b. Average Effective Chimney Heights

Fig. 1 shows isopleths of average effective heights for 50-m chimneys based on 1115 GMT rawinsondes. All of the values are within a rather narrow range, from 126 m at Ely, Nevada to 242 m at San Diego, California. There is some tendency for higher heights along coastlines, especially along the Pacific coast. Although it is not evident in Fig. 1, the value of 193 m for New York City (J. F. Kennedy Airport) is some 20 m higher

*The rawinsonde balloons usually were released 45 minutes before the scheduled observation times.

†The summary of rawinsonde observations (Holzworth, 1974b) only considered inversions within the lower 3000 m.

than at adjacent stations and may be due, at least in part, to the metropolitan heat island. The value for Burwood, Louisiana is also relatively high (199 m), but is probably caused by the station location on the Mississippi delta.

Fig. 2 shows isopleths of average effective heights for 400-m chimneys at 1115 GMT. Again the range of heights is rather limited, from 638 m at Oklahoma City to 795 m at Medford, Oregon. The area in the plains with heights less than 650 m appears to be related to relatively fast winds in that region. The presence of lower heights along the California coast is a reversal of the isopleth gradient for 50-m chimneys. It may be partly attributed to the high frequency of elevated inversions along the coast. It is interesting that the anomaly at New York City for small chimneys does not show up for large chimneys, as expected.

Fig. 3 shows the isopleth pattern of average effective heights at 2315 GMT for 50-m chimneys. Compared to morning, the afternoon values have a much wider range, from 169 m at Nantucket, Massachusetts to 718 m at Winslow, Arizona. The heights tend to be lower along coastlines than inland, and they tend to be higher over preferred regions of elevated terrain. It should be reemphasized that especially over irregular terrain the isopleths should be used only as general guidelines. For 400-m chimneys at 2315 GMT (Fig. 4) the isopleth pattern is similar to that for 50-m chimneys (Fig. 3). The range of afternoon heights for large chimneys is from 701 m at Nantucket to 1095 m at Winslow, which is considerably less than the range for small chimneys. This difference is shown generally by the isopleths in Figs. 3 and 4. It is caused mainly by the fact that in the afternoon the lower atmosphere, where small plumes are emitted, is usually less stable (superadiabatic in some cases) than the atmosphere at high levels where large plumes are emitted. Accordingly, small plumes lose buoyancy less rapidly (gain buoyancy in some cases) than do large plumes near levels where they are emitted. In the western United States the effective heights at 2315 GMT are probably representative of the diurnal maxima, but in the eastern states the diurnal maxima are probably somewhat greater than shown, especially for small chimneys.

c. Morning Effective Chimney Heights and Afternoon Mixing Heights

At most stations more than 95% of the effective heights for small chimneys at 1115 GMT are subsequently exceeded by the afternoon mixing height. The lowest frequency is 88% (at Nantucket) and only eight other stations have frequencies less than 95%, none of them less than 92%. Clearly, the afternoon mixing height usually exceeds the height of small morning plumes, enhancing contact with the ground and plume depletion. However, for 400-m chimneys the corresponding frequencies are considerably less, as shown in Fig. 5. The frequency at almost all stations is less than 90%. It is generally around 50% along the California coast and is relatively low along the Atlantic and central Gulf coasts. For the highly populated regions east of the Mississippi River, the difference in percentage between small and large morning plumes being subsequently reached by afternoon mixing heights is generally 15-25. Thus, the effluent from large chimneys tends to remain airborne longer than that from small chimneys.

d. Effective Chimney Heights in or Above Inversion

Since low-level inversions are very common at night and in the early morning (Hosler, 1961), a very high frequency of small and large plumes in or above inversions is expected for the 1115 GMT soundings. As shown in Fig. 6, there is also a significant occurrence of such plume configurations for the 2315 GMT soundings and 50-m chimneys. These optimum conditions for inhibiting plume contact with the ground in the afternoon/early evening occur in 20-40% of the observations in the eastern United States and in more than 40% along the southern California coast. Notice that again New York City (J. F. Kennedy Airport) shows up as an anomaly in the isopleth pattern. In general, the values for 400-m chimneys (not shown) are about 10% greater than those for 50-m chimneys (Fig. 6).

e. Morning Effective Chimney Heights in or Below Inversion and Subsequently Exceeded by Afternoon Mixing Heights

Percentage isopleths of the above subject conditions are shown in Fig. 7 for 50-m chimneys. These features are indicative of fumigating plumes during some part of the interval from shortly after sunrise to about mid-afternoon, and are highly favorable for enhancing plume contact with the ground. For 50-m chimneys these conditions occur in less than 50% of the observations only at Burwood; their occurrence exceeds 70% at most locations. For 400-m chimneys (Fig. 8) fumigating plumes are much less frequent than for 50-m chimneys. The highest percentage (49) is at San Antonio, Texas. Most of the large plume values are less than 35%. The difference in percent frequency between small and large fumigating plumes is generally around 50. It is due largely to the fact that many of the effective heights for large chimneys are above the inversion top. Consequently, large chimneys tend to delay contact of their plumes with the ground.

4. SUMMARY AND CONCLUSIONS

Briggs' plume rise equations were used with twice-daily rawinsonde observations to calculate effective heights for 50- and 400-m chimneys, and to infer plume configurations. A detailed summary for Salt Lake City is presented in Table 1. Based on rawinsonde observations at 62 National Weather Service stations in the contiguous United States, isoplethed maps of average effective chimney heights are presented for 50- and 400-m chimneys. In general, the ranges of annual average effective chimney heights are as follows:

	1115 GMT	2315 GMT
50-m Chimneys	150-200 m	200-700 m
400-m Chimneys	650-750 m	700-1100 m

At 1115 GMT the ranges for small and large chimneys are rather narrow. At 2315 GMT the ranges are broader; they are broadest for small chimneys. This is attributed mainly to less stable thermal structure in the afternoon near the ground where small plumes are emitted.

Plume configurations were inferred from the temperature structure at the effective chimney heights and from comparisons of morning effective chimney heights and afternoon mixing heights. Practically all of the effective heights for 50-m chimneys at 1115 GMT were subsequently reached by the afternoon mixing height, suggesting fumigating plumes during some part of the intervening period, but over the eastern United States large plumes were correspondingly reached only 75-85% of the time. Large plumes were more often in or above an inversion than small plumes. Clearly, large plumes tend to remain airborne longer than small plumes. With a trend to larger chimneys we may expect a trend of longer-range transport and associated pollution problems.

While the data presented in this paper are considered to be of considerable practical use, their limitations should not be overlooked. For example, the rawinsonde data, which were used to calculate plume rise, sometimes fail to include details that could be important in specific cases. The analyzed temperature soundings (Holzworth, 1974b), which were used to categorize stability at a plume's effective height, only listed the major features of each sounding. Afternoon mixing heights (Holzworth, 1972) were calculated under the assumption of a dry adiabatic lapse rate extending upward from the surface temperature. The possible effects of precipitation were not considered. Plume rise calculations were for the centerline of the plumes; their finite size was neglected. With these limitations, the data presented in this paper are most appropriately interpreted as climatological in which the statistics balance out the non-conforming situations. Application of the techniques described in this paper to specific cases should only be done with attention to the inherent limitations.

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Table 1. ANNUAL STATISTICS ON CALCULATED EFFECTIVE CHIMNEY HEIGHTS, SALT LAKE CITY, UTAH, 1960-1964

RAWINSONDE RELEASE	0415 MST		1615 MST	
PHYSICAL CHIMNEY SIZE (m)	50	400	50	400
AVG. HEAT EMISSION (10^6 cal sec^{-1})	2.8	41.7	2.7	40.7
AVG. EFFECTIVE HEIGHT (m)	148	752	356	915
RANGE (m)*	75–350	550–1375	125–2500	450–2500
STANDARD DEVIATION (m)*	46	112	242	252
BELOW INVERSION (%)	5	2	21	16
IN INVERSION (%)	67	10	8	7
ABOVE INVERSION (%)	19	79	1	7
NO INVERSION (%)	9	9	70	70
TOTAL CASES $H_a > H_e$ (%)**	97	76	93	73

*APPROXIMATED FROM CLASS INTERVAL FREQUENCIES.

**H_a = AFTERNOON MIXING HEIGHT, H_e = EFFECTIVE CHIMNEY HEIGHT.

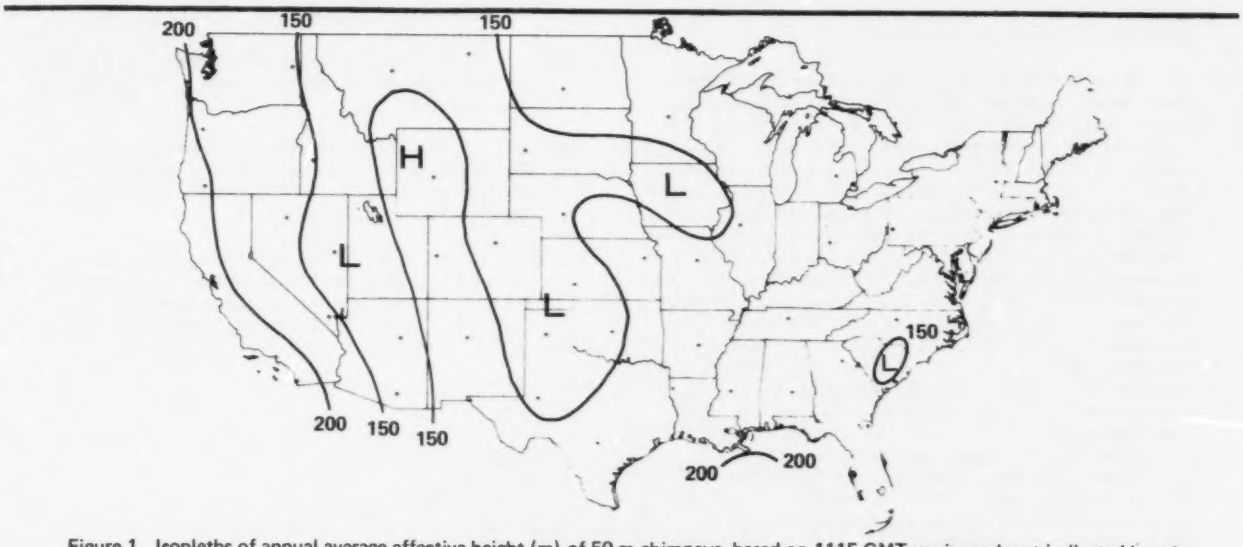

Figure 1. Isopleths of annual average effective height (m) of 50-m chimneys, based on 1115 GMT rawinsondes at indicated locations. See text for further details.

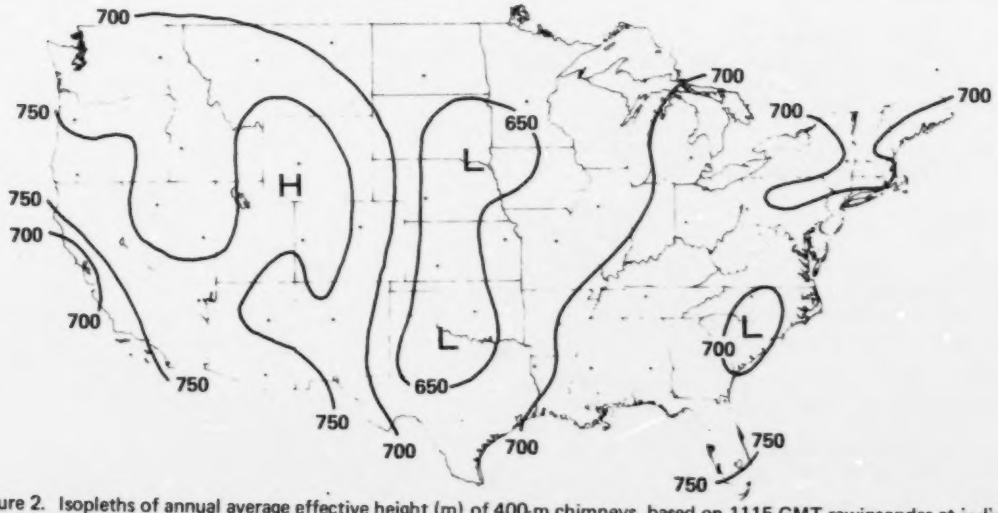

Figure 2. Isopleths of annual average effective height (m) of 400-m chimneys, based on 1115 GMT rawinsondes at indicated locations. See text for further details.

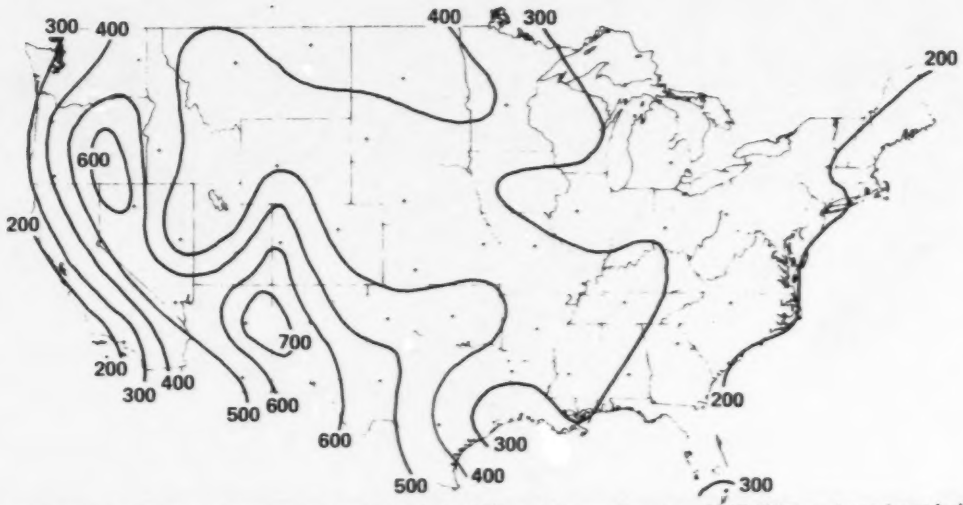

Figure 3. Isopleths of annual average effective height (m) of 50-m chimneys, based on 2315 GMT rawinsondes at indicated locations. See text for further details.

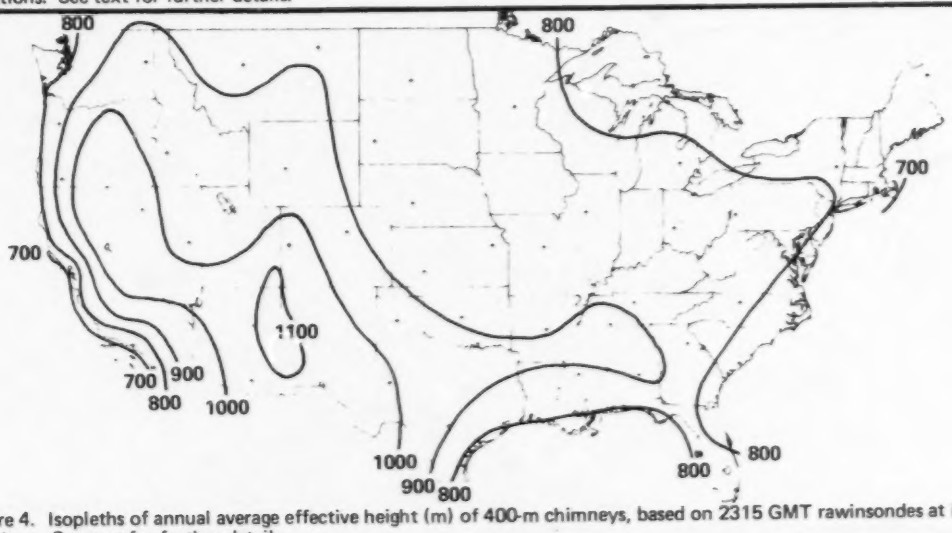

Figure 4. Isopleths of annual average effective height (m) of 400-m chimneys, based on 2315 GMT rawinsondes at indicated locations. See text for further details.

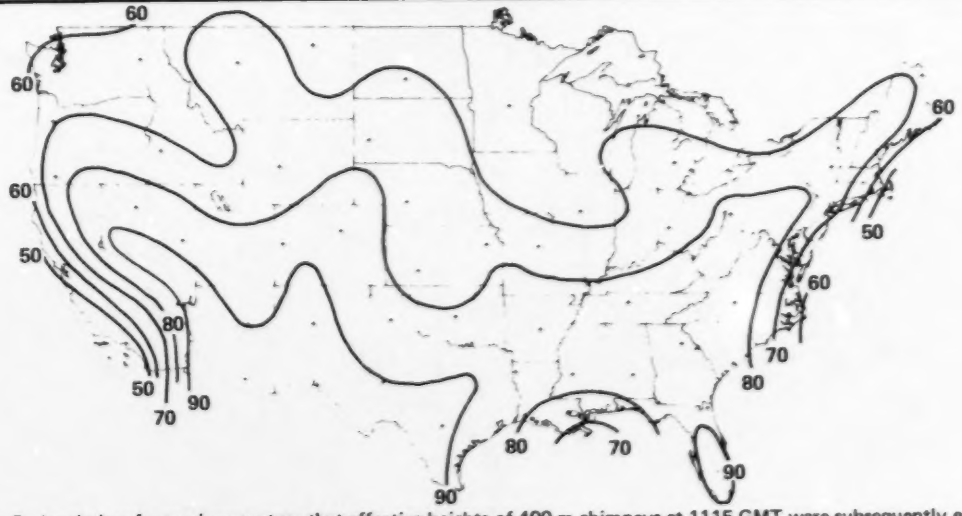

Figure 5. Isopleths of annual percentage that effective heights of 400-m chimneys at 1115 GMT were subsequently exceeded by the afternoon mixing height, based on rawinsondes at indicated locations.

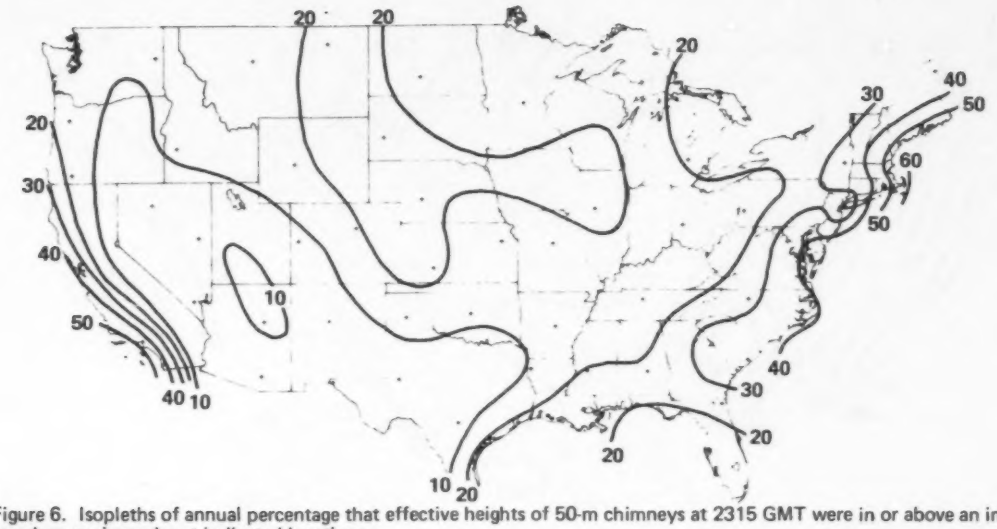

Figure 6. Isopleths of annual percentage that effective heights of 50-m chimneys at 2315 GMT were in or above an inversion, based on rawinsondes at indicated locations.

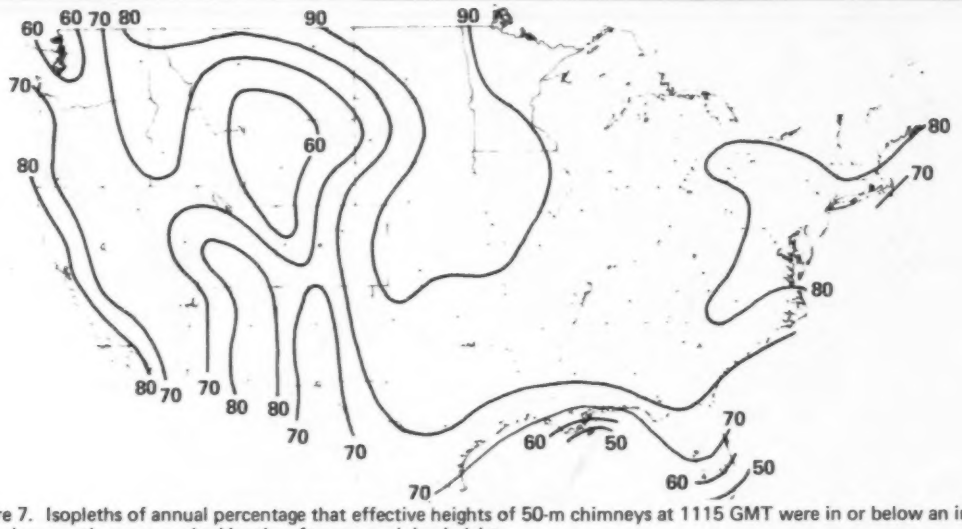

Figure 7. Isopleths of annual percentage that effective heights of 50-m chimneys at 1115 GMT were in or below an inversion and subsequently were reached by the afternoon mixing height.

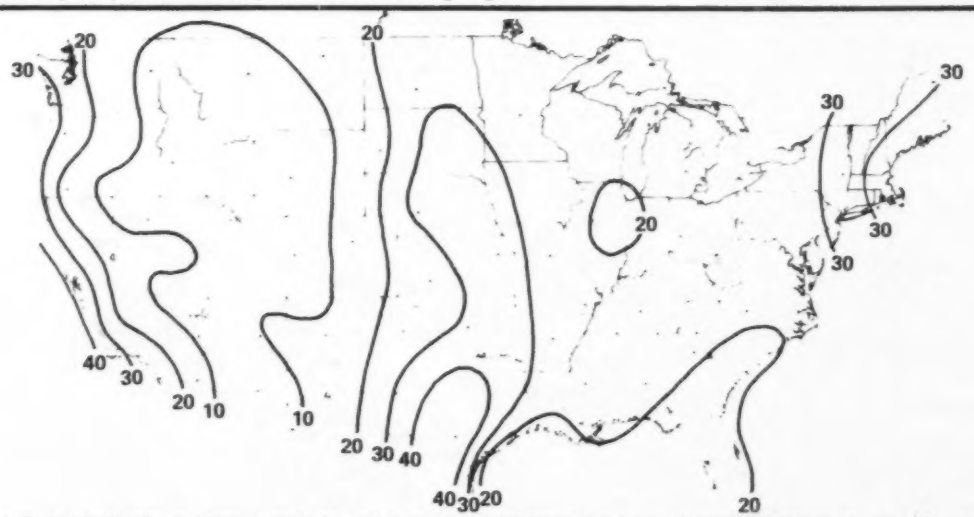

Figure 8. Isopleths of annual percentage that effective heights of 400-m chimneys at 1115 GMT were in or below an inversion and subsequently were reached by the afternoon mixing height.